

Simulations and Analysis of Sagged Cables/Mass Suspensions and Beams Subject to Flow Induced Vibrations

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Grant #: N00014-95-0256

LONG-TERM GOALS

The long-term goals of this research are to: (1) Develop and establish direct numerical simulation (DNS) and large-eddy simulation (LES) methods for flow-induced vibration of flexible structures; (2) Develop a theory that connects the hydrodynamic parameters of the wake and the structure's vibrations; and (3) Develop reduced dynamical models for predicting the dynamics of the coupled system.

OBJECTIVES

The general objective of the present program is to bridge the gap that exists between studies of nonlinear dynamic models for general type cables developed by other researchers and direct numerical simulations of flow past simple string/beam models developed in the previous phase of this grant. The former typically assumes a simplistic or empirical representation of excitation forces but provides very accurate models for the nonlinear dynamic response of the cable, allowing realistic description of both steel cables and synthetic cables with *nonlinear* tension-strain relationship. The latter, on the other hand, assumes simple string/beam linear models but provides an accurate description of pressure and viscous forces, albeit (at present) in the low Reynolds number regime. The specific objectives of our work are to:

1. Develop a hierarchy of simulation models of cables consisting for three-dimensional linear, weakly nonlinear, and fully nonlinear responses.
2. Incorporate geometric changes and nonlinear/hysteric tension-strain relationships into the models.
3. Study the response of general shape risers to VIV in conjunction with parallel experimental efforts.
4. Study the response of cables/risers with attached bodies following earlier experimental work at the Naval Research Laboratory (NRL).
5. Construct low-dimensional nonlinear dynamical models for VIV prototype cases.

APPROACH

The technical approach in addressing the aforementioned issues consists of two main parts: (1) The development and implementation of high-order numerical methods for DNS and LES in time-dependent domains; and (2) The construction of reduced dynamical systems using proper orthogonal decomposition and nonlinear Galerkin methods. In the first category, we have developed spectral methods on unstructured grids and two different ways of treating moving domains. The first one uses a boundary fitted coordinate system, and the second uses a third reference frame moving at an arbitrary velocity – the so-called Arbitrary Lagrangian Eulerian (ALE) formulation. The novelty of our ALE formulation is the development of a fast algorithm to update the grid velocity based on graph theory. In the second category, we have developed the equivalent method of snapshots to extract the most energetic modes of an unsteady field in both stationary and moving domains. The novelty of this part is the development of nonlinear Galerkin models that allow master-slaves combinations and lead to significant reduction in the dimensionality of the coupled system. These developments have been integrated in the parallel code NEKTAR-ALE, which has been ported on all available parallel systems including PC/LINUX clusters. A new development that could potentially increase efficiency of DNS by two orders of magnitude is the formulation of semi-Lagrangian schemes for the discretization of the advection contributions. The results so far suggest that the CFL constraint is bypassed and very large time steps can be used without loss of temporal accuracy.

WORK COMPLETED

We have derived a new generalized governing equation of motion for a general cylindrical structure with sag and have obtained a hierarchy of simulation models of cables consisting of linear three-dimensional, weakly nonlinear, and fully nonlinear responses. A generalized Hook's law is involved that allows a variation of Poisson ratio from 0 to 0.5. We have incorporated these models to NEKTAR-ALE and have assigned the solution of the structure's equations to a separate set of processors for enhanced modularity. In order to validate the new formulation we have repeated simulations of the laminar flow past a linear cable and compared with our previous results. In addition to the DNS formulation, we have developed an LES formulation that allows to increase the Reynolds number with the same resolution by about an order of magnitude. We have developed a new LES approach based on the concept of spectral vanishing viscosity (SVV) that maintains the high-accuracy of the spectral discretization while it preserves monotonicity of the high modes of the solution. Specifically, the theory provides the limits of the amplitude and wavenumber cutoff unlike the classical LES approach where the limits are calibrated empirically. We have performed several simulations based on SVV-LES at a Reynolds number above 100,000 for single stationary cylinders and up to 10,000 for vibrating cylinders. We have also performed DNS and SVV-LES for shear inflow past flexible cables and beams as well as nonlinear structures such as the "lazy wave riser".

RESULTS

We have obtained:

1. DNS results of shear flow past *linear* flexible cables and beams at $Re=1000$ and $10,000$:
 - Mild (linear) shear inflow induces fully locked-in response for a long cable in agreement with experiments conducted in Norway (lock-in of mode 3). Strong (exponential) shear

induces multi-mode response with excited modes as high as 12-14. These results too agree with experimental data available in the oil industry.

- The flow field in the near-wake is populated by vortex dislocations and vortex splits. Verification of the presence of these structures obtained in the experiments of Williamson (vortex dislocations) and of Triantafyllou (vortex splits) was achieved both for forced and for free vibrations.
- The force distribution along the cable/beam axis is affected significantly by vortex splits and vortex dislocations as strong low-frequency modulations are present in the regions around these structures, and many cellular shedding patterns emerge, especially for cables/beams with very large aspect ratio.
- Existing semi-empirical models cannot predict accurately VIV with shear inflow as the correlation length is modified substantially by the presence of these flow structures.

2. DNS and LES results of turbulent flow past a stationary cylinder at $Re=3900$:

- A systematic comparison between spectral DNS, spectral LES and low-order LES (available in the literature) showed that the discretization scheme may interfere with the subgrid model producing erroneous answers. High-resolution DNS as well as SVV-LES predict accurately the wake's turbulence statistics unlike conventional LES employed in equilibrium turbulence. These results suggest that SVV-LES can be employed successfully to simulate VIV in realistic Reynolds numbers in the subcritical regime.
- The turbulent wake of stationary cylinders was found to be low-dimensional by studying phase-averaged statistics and the eigenspectrum of the vorticity covariance matrix. The results suggest that a dynamical model would require of the order of twenty modes to describe the near-wake dynamics with reasonable accuracy for Re up to 5000. Non lock-in states require significantly greater number of modes for accurate simulations.

3. DNS results of laminar flow past *nonlinear* cables (catenary and lazy wave risers) at $Re=100$ and 1,000. Based on the analysis of these results we have concluded:

- The cable tension shows considerable variability with time and to a lesser extent along the span, giving rise to non-classical lock-in phenomena.
- The coupled flow-structure system is very sensitive to large tension variations in the initial conditions.
- Significant hydrodynamic forces can develop along the spanwise direction (cable axis) giving rise to non-negligible longitudinal oscillations.
- Lazy wave risers develop axial oscillations in the form of traveling waves. Accurate simulation of their performance requires fully nonlinear flow-structure interaction models.

IMPACT/APPLICATIONS

Our work has established a new area of DNS and LES for flow-structure interactions and has produced the first ever such results both in laminar and turbulent regime. New findings have obtained, such as the mixed traveling/standing wave response for vibrating cables, which have become the focus of

several experimental and modeling efforts. More recently the construction of detailed databases for force distribution for vibrating cables and beams in uniform and shear inflows has provided a valuable source for developing simpler engineering models. With the emergence of the PC Linux clusters and simultaneous advances in algorithms and software, we expect that these methods will become very efficient so that they can soon be used effectively in the design process by the navy labs and the industry.

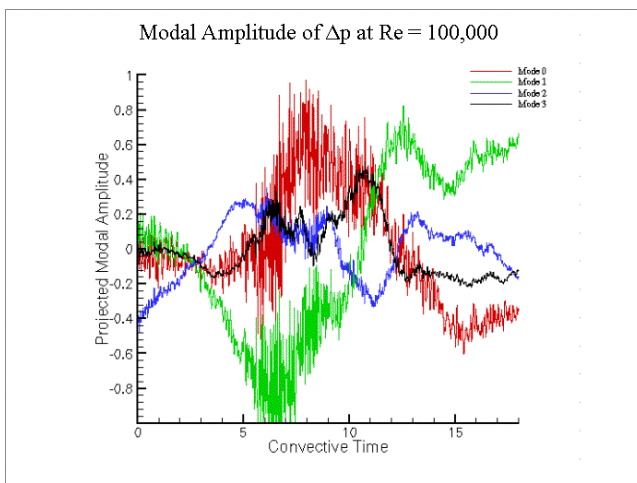
TRANSITIONS

The findings related to long cables regarding shear flow effects and multi-moded response and the detailed spatio-temporal distribution of forces on the vibrating structure are directly useful in military applications as well as the offshore industry. We have been working with a consortium of oil industries in US (Chevron) and with Norsk Hydro (Norway) to address their specific problems using the techniques we have developed. In addition, we have released our code NEKTAR-ALE to many other Universities and national labs, including: MIT, Caltech, Cornell University, WPI, Florida State University, Oak Ridge National Labs, University of Wisconsin, Imperial College, Oxford University, Boeing, Inc., Penn State University, Washington State University, Nielsen Inc., Sandia National Labs, etc. We have trained more than one dozen researchers last year in the methods and the software that we have been developing.

RELATED PROJECTS

We have been working closely with experimental groups funded by the same Division under the direction of Dr. T.F. Swean. In particular, we have had interactions with Profs. Triantafyllou and Yue at MIT; Prof. Gharib at Caltech; Prof. Williamson at Cornell; and Prof. Olinger at WPI. In the past two years, we have worked very closely with the MIT and WPI groups to port NEKTAR-ALE on computers at their sites as well as at supercomputer centers.

In addition, we have worked with Ocean Power Technology Inc. to optimize the design of an energy-extraction device, named the energy-harvesting eel. This project is described in some detail next:



NEKTAR-ALE

Pressure records on the flexible membrane at high Reynolds number. Plotted are the amplitudes of the pressure force obtained by projecting the force onto the linear vibration modes.

Simulations of Flow Past an Energy-Harvesting Eel

In this project, the objective is to exploit the periodic motion produced by vortex shedding in flow past a bluff body. To this end, Ocean Power Technology, Inc. (OPT) has proposed to place a piezoelectric membrane in the near wake of a flat plate (bluff body). This membrane is subject to periodic pressure variation on both sides due to alternating von Karman vortices. The maximum energy stored in the membrane scales proportionally with the frequency and the amplitude of membrane's oscillation. It is therefore desirable to choose the various parameters so that the coupled system operates at lock-in. In this study, we have been investigating effects due to bluff body/membrane spacing, the membrane length, and the Reynolds number. Depending on the membrane's stiffness a different mode is excited, but typically the first and second mode coexist. The optimum conditions seem to correspond to excitation of the second mode. The two main developments in the last year were: (1) The formulation of nonlinear structural models for the membrane that preserve the length of the membrane, and (2) Simulation of high Reynolds number flows matching exactly the experimental conditions. In the figure above the driving pressure force is plotted at different times after projected onto linear vibration modes. Clearly, a multi-mode response is obtained for these conditions.

We have been working closely with the experimental group of Prof. A.J. Smits at Princeton University for a complete numerical-experimental optimization study of this energy-extraction device.